Manifestations of CP Violation in the MSSM Higgs Sector

Jae Sik Lee [a,b,c]

[a] *Physics Division, National Center for Theoretical Sciences, Hsinchu, Taiwan*
[b] *Department of Physics and Center for Mathematics and Theoretical Physics, National Central University, Chung-Li, Taiwan*
[c] *Institute of Physics, Academia Sinica, Taipei, Taiwan*

Abstract. We demonstrate how CP violation manifests itself in the Higgs sector of the minimal supersymmetric extension of the Standard Model (MSSM). Starting with a brief introduction to CP violation in the MSSM and its effects on the Higgs sector, we discuss some phenomenological aspects of the Higgs sector CP violation based on the two scenarios called *CPX* and *Trimixing*.

Keywords: Higgs, CP, SUSY
PACS: 14.80.Cp, 11.30.Er, 12.60.Jv

INTRODUCTION

The single Kobayashi-Maskawa phase [1] in the Standard Model (SM) seems to explain almost all the laboratory data available so far [2]. Nevertheless, there seems to be a general agreement that it is too weak to explain the observed baryon asymmetry of the Universe [3]. As one of the most appealing scenarios for New Physics beyond the SM, Supersymmetry (SUSY) might include sufficient non-SM CP-violating sources enabling successful baryogenesis at the electroweak scale [4, 5]. We study the phenomenological implications of the SUSY CP phases through the productions and decays of the Higgs bosons in the MSSM framework.

CP VIOLATION IN THE HIGGS SECTOR

In the MSSM, CP-violating phases appear in the μ term of the superpotential, $W \supset \mu \hat{H}_2 \cdot \hat{H}_1$, and in the soft-SUSY breaking terms as follows:

$$\begin{aligned} -\mathscr{L}_{\rm soft} \supset\ & \frac{1}{2}(M_3 \widetilde{g}\widetilde{g} + M_2 \widetilde{W}\widetilde{W} + M_1 \widetilde{B}\widetilde{B} + {\rm h.c.}) \\ & + \widetilde{Q}^\dagger \mathbf{M}^2_{\widetilde{\mathbf{Q}}} \widetilde{Q} + \widetilde{L}^\dagger \mathbf{M}^2_{\widetilde{\mathbf{L}}} \widetilde{L} + \widetilde{u}^*_R \mathbf{M}^2_{\widetilde{\mathbf{u}}} \widetilde{u}_R + \widetilde{d}^*_R \mathbf{M}^2_{\widetilde{\mathbf{d}}} \widetilde{d}_R + \widetilde{e}^*_R \mathbf{M}^2_{\widetilde{\mathbf{e}}} \widetilde{e}_R \\ & + (\widetilde{u}^*_R \mathbf{A_u} \widetilde{Q} H_2 - \widetilde{d}^*_R \mathbf{A_d} \widetilde{Q} H_1 - \widetilde{e}^*_R \mathbf{A_e} \widetilde{L} H_1 + {\rm h.c.}) \\ & - (m^2_{12} H_1 H_2 + {\rm h.c.})\,. \end{aligned} \tag{1}$$

Assuming flavour conservation, there are 14 CP phases including that of the Higgsino mass parameter μ. It turns out they are not all independent and the physical observables depend on the two combinations [6]

$${\rm Arg}(M_i\,\mu\,(m^2_{12})^*)\,, \quad {\rm Arg}(A_f\,\mu\,(m^2_{12})^*)\,, \tag{2}$$

with $i = 1-3$ and $f = e,\mu,\tau;u,c,t,d,s,b$. In the convention of real and positive μ and m^2_{12}, the most relevant CP phases pertinent to the Higgs sector are

$$\Phi_i \equiv {\rm Arg}(M_i)\,; \quad \Phi_{A_{f_3}} \equiv {\rm Arg}(A_{f_3})\,, \tag{3}$$

with $f_3 = \tau, t, b$.

The Higgs sector of the MSSM consists of two doublets:

$$H_1 = \begin{pmatrix} H_1^0 \\ H_1^- \end{pmatrix}; \quad H_2 = \begin{pmatrix} H_2^+ \\ H_2^0 \end{pmatrix}. \tag{4}$$

The neutral components can be rewritten in terms of 4 real field as

$$H_1^0 = \frac{1}{\sqrt{2}}(\phi_1 - i a_1)\,, \quad H_2^0 = \frac{1}{\sqrt{2}}(\phi_2 + i a_2)\,, \tag{5}$$

where $\phi_{1,2}$ and $a_{1,2}$ are CP-even and CP-odd fields, respectively. After the electroweak symmetry breaking, $\langle\phi_1\rangle = v\cos\beta$ and $\langle\phi_2\rangle = v\sin\beta$, we are left with 5 Higgs states: 2 charged and 3 neutral. The 3 neutral states consists of one CP-odd state, $A = -a_1\sin\beta + a_2\cos\beta$, and two CP-even ones, h and H. The mixing between the two CP-even states is described by the 2×2 matrix with the mixing angle α as

$$\begin{pmatrix} h \\ H \end{pmatrix} = \begin{pmatrix} \cos\alpha & -\sin\alpha \\ \sin\alpha & \cos\alpha \end{pmatrix} \begin{pmatrix} \phi_2 \\ \phi_1 \end{pmatrix}. \tag{6}$$

This is what we know in the absence of CP phases.

The story becomes different in the presence of CP phases. The non-vanishing CP phases of third generation A terms could radiatively induce significant mixing between the CP-even and CP-odd states proportional

to [7, 8]

$$\frac{3m_f^2}{16\pi^2}\frac{\Im\mathrm{m}(A_f\,\mu)}{(m_{\tilde f_2}^2-m_{\tilde f_1}^2)}\,. \tag{7}$$

The CP phase of the gluino mass parameter also contribute the CP-violating mixing through the so-called threshold corrections

$$h_b=\frac{\sqrt{2}m_b}{v\cos\beta}\,\frac{1}{1+\kappa_b\tan\beta}\,, \tag{8}$$

where

$$\begin{aligned}\kappa_b &= \frac{2\alpha_s}{3\pi}M_3^*\mu^* I(m_{\tilde b_1}^2,m_{\tilde b_2}^2,|M_3|^2)\\ &+ \frac{|h_t|^2}{16\pi^2}A_t^*\mu^* I(m_{\tilde t_1}^2,m_{\tilde t_2}^2,|\mu|^2)\,,\end{aligned} \tag{9}$$

with

$$I(x,y,z) = \frac{xy\ln(x/y)+yz\ln(y/z)+xz\ln(z/x)}{(x-y)\,(y-z)\,(x-z)}\,. \tag{10}$$

It is formally two-loop effect but could be important when $\tan\beta$ is large.

Phenomenological consequences of the CP-violating mixing among the three neutral Higgs bosons are: (*i*) the neutral Higgs bosons do not have to carry any definite CP parities, (*ii*) the neutral Higgs-boson mixing is described by the 3×3 mixing matrix $O_{\alpha i}$ as $(\phi_1,\phi_2,a)^T = O_{\alpha i}(H_1,H_2,H_3)^T$ with $H_{1(3)}$ the lightest (heaviest) Higgs state, (*iii*) the couplings of the Higgs bosons to the SM and SUSY particles are significantly modified. There are many computational tools available for calculations within the MSSM. The first to include CP-violating phases was `CPsuperH` [9, 10] based on the renormalization-group-(RG-)improved effective potential approach. The recent versions of `FeynHiggs` [11] are based on the Feynman diagrammatic approach. In our numerical analysis, we use the code `CPsuperH`.

CPX SCENARIO

The CPX scenario is defined as [12]:

$$\begin{aligned}&M_{\tilde Q_3}=M_{\tilde U_3}=M_{\tilde D_3}=M_{\tilde L_3}=M_{\tilde E_3}=M_{\rm SUSY}\,,\\ &|\mu|=4M_{\rm SUSY}\,,\ \ |A_{t,b,\tau}|=2M_{\rm SUSY}\,,\ \ |M_3|=1\ \ \mathrm{TeV}.\end{aligned} \tag{11}$$

The parameter $\tan\beta$, the charged Higgs-boson pole mass $M_{H^\pm}$, and the common SUSY scale $M_{\rm SUSY}$ can be varied. For CP phases, taking a common phase $\Phi_A=\Phi_{A_t}=\Phi_{A_b}=\Phi_{A_\tau}$ for A terms, we have two physical phases to vary: Φ_A and $\Phi_3=\mathrm{Arg}(M_3)$.

In Fig. 1, we show the Higgs-boson pole masses and their couplings to two vector bosons normalized to the SM value as functions of Φ_A for three values of the charged Higgs-boson pole mass: 120 GeV (left frames), 160 GeV (middle frames), and 250 GeV (right frames). We observe, when $M_{H^\pm}=120$ GeV, M_{H_1} can be as light as a few GeV around $\Phi_A=\pm90^\circ$ where H_1 is almost CP odd with nearly vanishing coupling to two vector bosons. In the decoupling limit, $M_{H^\pm}=250$ GeV, the lightest Higgs boson is decoupled from the mixing but there could still be a significant CP-violating mixing between the two heavier states. In Fig. 2, we show the branching fractions and decay widths of the Higgs bosons when $\Phi_A=\Phi_3=90^\circ$. The decay patterns of the heavier Higgs states become complicated compared to the CP-conserving case due to the loss of its CP parities [14]. And, at its lower mass edges, they decay dominantly into two lightest Higgs bosons increasing the decay widths considerably, see the lower-right frame [1]. These features combined make the Higgs searches at LEP difficult, resulting in two uncovered holes on the $\tan\beta$-M_{H_1} plane when $M_{H_1}\lesssim10$ GeV and $M_{H_1}\sim30-50$ GeV for intermediate values of $\tan\beta$, as shown in Fig. 3. It seems difficult to cover the holes completely at the LHC [16]. In this case, to answer whether we should rely on the International Linear Collider (ILC) for the Higgs discovery [17], one might need to study the charged Higgs-boson decays more precisely as well as the cascade decays of SUSY particles into Higgs bosons.

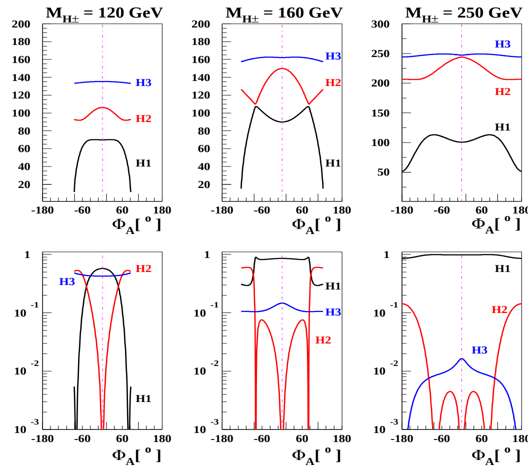

FIGURE 1. The Higgs-boson masses M_{H_i} (upper frames) in GeV and $g^2_{H_iVV}$ (lower frames) as functions of Φ_A for the CPX scenario for three values of the charged Higgs-boson pole mass when $\tan\beta=4$, $\Phi_3=0^\circ$, and $M_{\rm SUSY}=0.5$ TeV; from Ref. [13].

[1] In the case of the charged Higgs boson, it decays dominantly into $W^\pm$ and H_1.

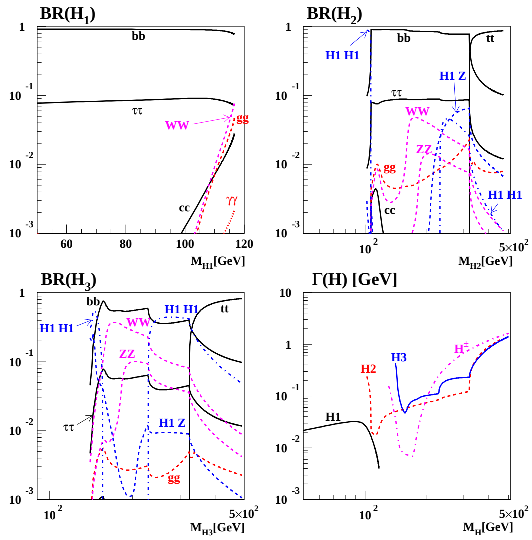

FIGURE 2. The branching fractions and decay widths of the MSSM Higgs bosons for the CPX scenario with $\tan\beta = 4$ and $M_{\rm SUSY} = 0.5$ TeV as functions of their masses when $\Phi_A = \Phi_3 = 90^\circ$; from Ref. [9].

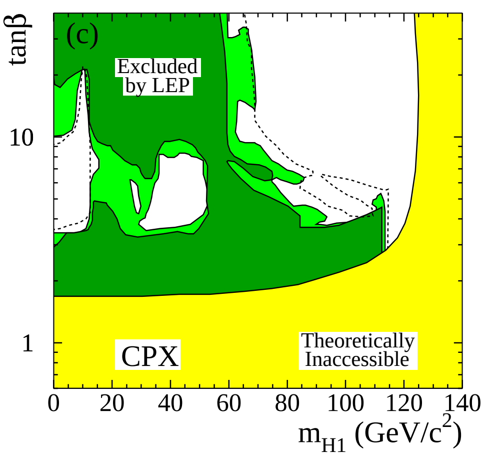

FIGURE 3. The LEP exclusion plot on the $\tan\beta$-M_{H_1} plane for the CPX scenario when $\Phi_A = \Phi_3 = 90^\circ$; from Ref. [15].

In the scenario with large $|\mu|$ and $|M_3|$ like as CPX, the threshold corrections significantly modify the relation between the down-type quark mass and the corresponding Yukawa coupling when $\tan\beta$ is large, see Eq. (8). The modification leads to strong CP-phase dependence of the b-quark fusion production of the neutral Higgs bosons. In Fig. 4, we show the inclusive production cross sections of H_1 and H_2 via b-quark fusion as functions of Φ_A. We

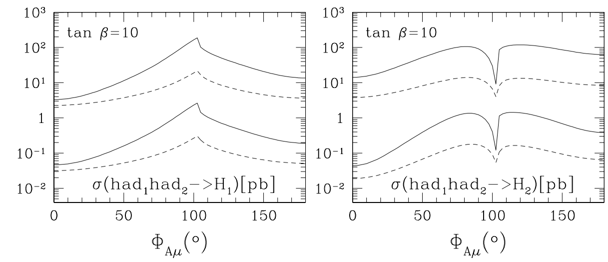

FIGURE 4. The inclusive production cross sections of H_1 and H_2 via b-quark fusion for the CPX scenario as functions of Φ_A when $\tan\beta = 10$ at the LHC (upper lines) and Tevatron (lower lines); from Ref. [18].

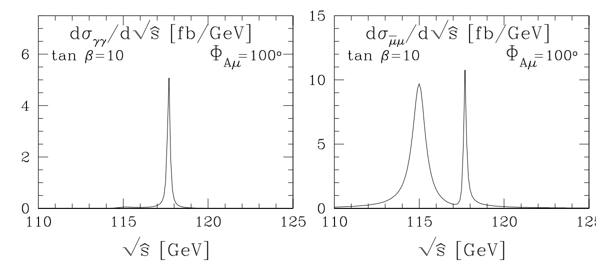

FIGURE 5. The LHC differential production cross sections of H_1 and H_2, produced via b-quark fusion and decaying into photons (left) and muons (right), for the same scenario as in Fig. 4 but with $\Phi_A = 100^\circ$ as functions of the invariant mass of two photons and two muons. We see only one peak in the photon decay mode (left) since H_1 with 115 GeV mass is almost CP odd; from Ref. [20].

see about a factor 100 enhancement in the H_1 production and the corresponding suppression in the H_2 production around $\Phi_A = 100^\circ$, where the mass difference between H_1 and H_2 is only $3-5$ GeV. Taking account of the good $\gamma\gamma$ and $\mu^+\mu^-$ resolutions of $1-3$ GeV at the LHC [19], the combined analysis of Higgs decays to photons and muons may help to resolve the two CP-violating adjacent peaks as illustrated in Fig. 5.

Low-energy precision experiments place important constraints on the CPX scenario. First of all, the non-observation of the Electric Dipole Moments (EDMs) of the Thallium (^{205}Tl) [22], neutron (n) [23], and Mercury (^{199}Hg) [24] already provides rather tight bounds on the CP-violating phases. In the upper frames of Fig. 6, we show the three EDMs, normalized to the current experimental limits, as functions of the common hierarchy factor ρ between the first two and third generations: $M_{\tilde{X}_{1,2}} = \rho\, M_{\tilde{X}_3}$ with $X = Q,U,D,L,E$. We take $\tan\beta = 5$ and several combinations of (Φ_1, Φ_2) with fixed $\Phi_A = \Phi_3 = 90^\circ$. As ρ increases, the EDMs decrease, develop dips, and saturate to certain values, becoming independent of ρ. In the case of Thallium EDM, the domi-

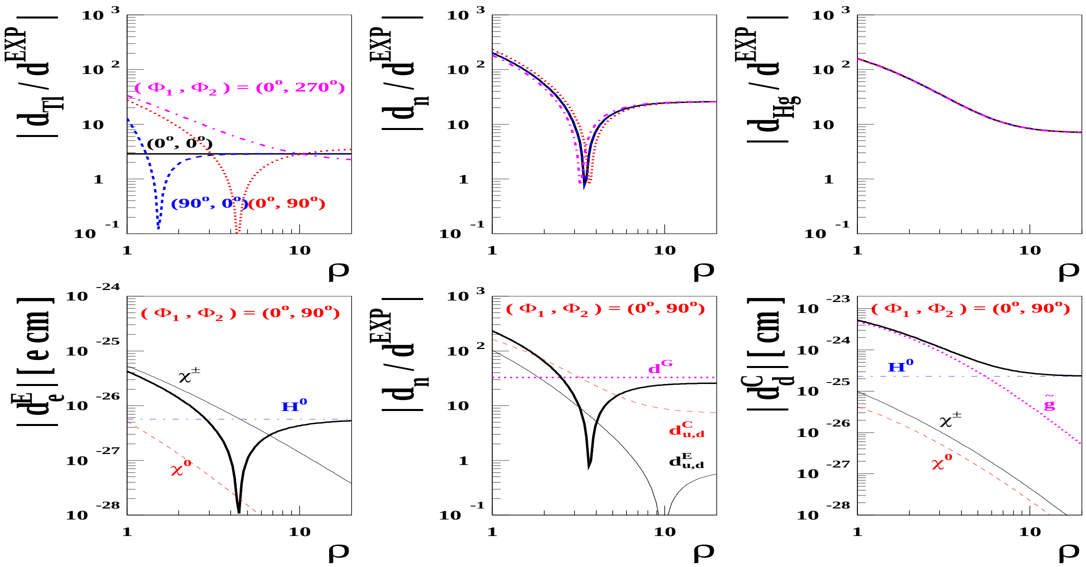

FIGURE 6. The Thallium (upper-left), neutron (upper-middle), and Mercury (upper-right) EDMs in the CPX scenario with $\tan\beta = 5$ and $\Phi_A = \Phi_3 = 90^\circ$ as functions of the common hierarchy factor ρ. In the lower frames, the most important constituent contributions to each EDM are shown taking $(\Phi_1, \Phi_2) = (0^\circ, 90^\circ)$; from Ref. [21].

nant contribution comes from the electron EDM. Taking $(\Phi_1, \Phi_2) = (0^\circ, 90^\circ)$, in the lower-left frame of Fig. 6, we show the dip around $\rho = 4$ is due to the cancellation between the one-loop chargino $(\chi^\pm)$ and the two-loop Higgs-mediated (H^0) contributions to the electron EDM. We find the neutron and Mercury EDMs are not so sensitive to $\Phi_{1,2}$. As shown in the lower-middle frame, the dominant contribution to the neutron EDM is coming from the dimension-six three-gluon Weinberg operator (d^G) and the EDM and chromoelectric dipole moment (CEDM) of the down quark $(d_d^{E,C})$. Cancellation among the three main contributions occurs around $\rho = 3$. But the ρ position where the cancellation occurs could change by $\sim \pm 1$ due to the uncertainty of the d^G contribution to the neutron EDM. In the lower-right frame, we show the constituent contributions to the CEDM of the down quark from which the Mercury EDM receives the main contribution. Around $\rho = 4$, the Mercury EDM is larger than the current experimental limit by a factor of about 10. But there is uncertainty of at least a factor of $3-4$ involved in the Mercury EDM calculation. Therefore, there is a possibility of evading all the three EDM constraints by taking $(\Phi_1, \Phi_2) = (0^\circ, 90^\circ)$ and $\rho \sim 4$ in the CPX scenario with $\Phi_A = \Phi_3 = 90^\circ$ when $\tan\beta = 5$. For more details, we refer to Ref. [21].

The more stringent constraint on the CPX scenario may come from the B-meson observables. In Fig. 7, we show the allowed regions on $\tan\beta$-M_{H_1} plane by the experimental constraints from $\Upsilon \to H_1\gamma$ (region to the right of the vertical line), $B(B_s \to \mu^+\mu^-)$ (lower-right region), $B(B \to X_s\gamma)$ (upper region), and $B(B^\pm \to \tau^\pm\nu)$ (two-band region connected by a narrow corridor). Note the lower limit on the lightest Higgs-boson mass of about 8 GeV comes from $\Upsilon \to H_1\gamma$. We observe there is no region in which the constraints from $B(B_s \to \mu^+\mu^-)$ and $B(B \to X_s\gamma)$ are satisfied simultaneously. Therefore, one may be tempted to conclude the CPX scenario has been ruled out by the B-meson data. But inclusion of flavour violation in the soft-SUSY breaking terms may change the predictions for the B-meson observables considerably, possibly allowing CPX as a phenomenological viable scenario in the MSSM framework.

TRIMIXING SCENARIO

The trimixing scenario is characterized by large $\tan\beta$ and a light charged Higgs boson, resulting in a strongly coupled system of the three neutral Higgs bosons with mass differences smaller than the decay widths [26]. In this scenario, the neutral Higgs bosons can not be treated separately and it needs to consider the transitions between the Higgs-boson mass eigenstates induced by the off-diagonal absorptive parts, $\Im\mathrm{m}\hat{\Pi}\big|_{i\neq j}(\hat{s})$. In Fig. 8, we show the absolute value of each component of the dimen-

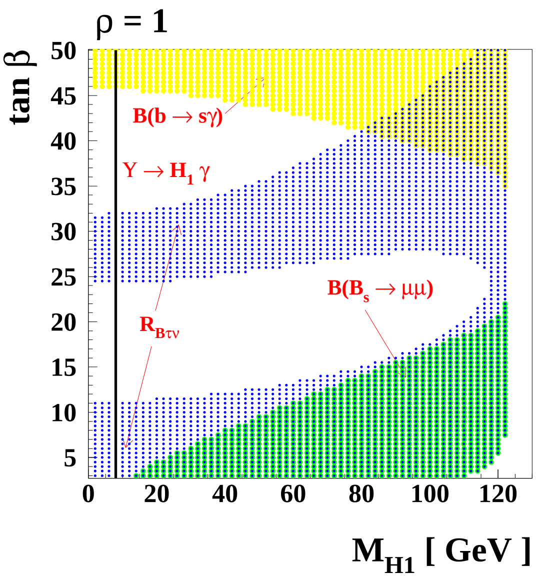

FIGURE 7. The allowed region on $\tan\beta$-M_{H_1} plane by the experimental constraints from $B(B_s \to \mu^+\mu^-)$ (95 %), $B(B \to X_s\gamma)$ (2 σ), and $R_{B\tau\nu}$ (1 σ). The region to the left of the vertical line is excluded by data on $\Upsilon \to H_1\,\gamma$ decay. The CPX scenario with $\Phi_A = \Phi_3 = 90^\circ$ is taken; from Refs. [25, 10].

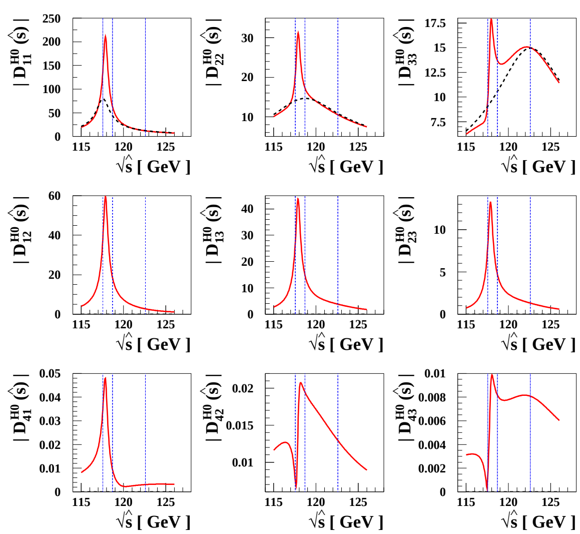

FIGURE 8. The absolute value of each component of the neutral Higgs-boson propagator matrix $D^{H^0}(\hat{s})$ with (red solid lines) and without (black dashed lines) including off-diagonal absorptive parts in the trimixing scenario with $\Phi_A = -\Phi_3 = 90^\circ$. We note that $|D^{H^0}_{44}(\hat{s})| = 1$. The three Higgs-boson pole masses are indicated by thin vertical lines; from Ref. [10].

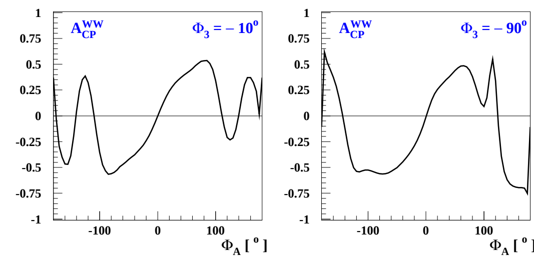

FIGURE 9. The CP asymmetry $\mathscr{A}_{\rm CP}^{WW}$ as functions of $\Phi_A = \Phi_{A_t} = \Phi_{A_b} = \Phi_{A_\tau}$ in the trimixing scenario with $\Phi_3 = -10^\circ$ (left) and -90° (right); from Ref. [26].

sionless 4×4 neutral Higgs-boson propagator matrix

$$D^{H_0}_{ij}(\hat{s}) \equiv \hat{s}\,[(\hat{s}-M_H^2)\,\mathbf{1}_{4\times4} + i\,\Im\mathrm{m}\hat{\Pi}(\hat{s})]^{-1}_{ij}\,, \qquad (12)$$

with $i,j = 1-4$ corresponding to H_1, H_2, H_3, and G^0. Compared to the case without including the off-diagonal elements (dashed lines in the upper frames), we observe that the peaking patterns are different (solid lines in the upper frames). We also note the off-diagonal transition can not be neglected (middle frames).

At the LHC, there may be a way to probe CP violation in the trimixing scenario, though it seems challenging. In the WW fusion production of the Higgs bosons decaying into tau leptons, the difference between the cross sections into the right-handed and left-handed tau leptons signals CP violation. The corresponding CP asymmetry turns out to be large over the whole range of Φ_A independently of Φ_3 in the trimixing scenario, as shown in Fig. 9.

CONCLUSIONS

The SUSY extensions of the SM contain many possible sources of CP violation beyond the CKM phase in the SM, which might be helpful to explain the baryon asymmetry of the Universe. The CP-violating phases could radiatively induce significant mixing between the CP-even and CP-odd Higgs states. In turns out that the CP-violating mixing could make the Higgs boson lighter than 50 GeV elusive at LEP and even at the LHC, specifically in the CPX scenario. In the scenario, when $\tan\beta$ is intermediate or large, the production cross sections of the neutral Higgs bosons via b-quark fusion strongly depend on the CP phases due to the threshold corrections and the CP-violating Higgs mixing. At the LHC, it might be possible to disentangle two adjacent CP-violating Higgs peaks by exploiting its decays into photons and muons unless the mass difference is smaller than 1 or 2 GeV. The constraints on the CPX scenario

from the non-observation of the Thallium, neutron, Mercury EDMs can be evaded by invoking cancellation and it might be possible to avoid the constraints from the precision experiments on B meson by introducing flavour violation in the soft-SUSY breaking sector.

We present the general formalism for a coupled system of CP-violating neutral Higgs bosons at high-energy colliders. It is suggested to measure the polarizations of the tau leptons in the process $W^+W^- \to H_{i\oplus j} \to \tau^+_{R,L}\tau^-_{R,L}$ to probe the Higgs-sector CP violation at the LHC. The study of the final state spin-spin correlations of tau leptons, neutralinos, charginos, top quarks, vector bosons, stops, etc are crucial for proving SUSY itself as well as for the CP studies of the Higgs bosons at the LHC. We need to implement complementary studies on the SUSY CP phases through the productions and decays of SUSY particles other than Higgs bosons [27].

ACKNOWLEDGMENTS

I wish to thank F. Borzumati, M. Carena, S.Y. Choi, M. Drees, K. Hagiwara, J. Ellis, A. Pilaftsis, S. Scopel, J. Song, W.Y. Song, C.E.M. Wagner for valuable collaborations. This work was supported in part by the National Science Council of Taiwan, R.O.C. under Grant No. NSC 96-2811-M-008-068.

REFERENCES

1. M. Kobayashi and T. Maskawa, Prog. Theor. Phys. **49** (1973) 652.
2. See, for example, M. Bona *et al.* [UTfit Collaboration], JHEP **0610** (2006) 081 [arXiv:hep-ph/0606167]; J. Charles *et al.* [CKMfitter Group], Eur. Phys. J. C **41** (2005) 1 [arXiv:hep-ph/0406184].
3. See, for example, J. M. Cline, arXiv:hep-ph/0609145 and references therein.
4. V. A. Kuzmin, V. A. Rubakov and M. E. Shaposhnikov, Phys. Lett. B **155** (1985) 36; A. G. Cohen, D. B. Kaplan and A. E. Nelson, Nucl. Phys. B **349** (1991) 727; M. Joyce, T. Prokopec and N. Turok, Phys. Lett. B **339** (1994) 312; M. Quiros, Helv. Phys. Acta **67** (1994) 451; V. A. Rubakov and M. E. Shaposhnikov, Usp. Fiz. Nauk **166** (1996) 493 [Phys. Usp. **39** (1996) 461] [arXiv:hep-ph/9603208]; M. S. Carena and C. E. M. Wagner, arXiv:hep-ph/9704347; A. Riotto and M. Trodden, Ann. Rev. Nucl. Part. Sci. **49** (1999) 35 [arXiv:hep-ph/9901362].
5. G. F. Giudice, Phys. Rev. D **45** (1992) 3177; S. Myint, Phys. Lett. B **287** (1992) 325 [arXiv:hep-ph/9206266]; J. R. Espinosa, M. Quiros and F. Zwirner, Phys. Lett. B **307** (1993) 106 [arXiv:hep-ph/9303317]; A. Brignole, J. R. Espinosa, M. Quiros and F. Zwirner, Phys. Lett. B **324** (1994) 181 [arXiv:hep-ph/9312296]; M. S. Carena, M. Quiros and C. E. M. Wagner, Phys. Lett. B **380** (1996) 81 [arXiv:hep-ph/9603420]; M. S. Carena, M. Quiros and C. E. M. Wagner, Nucl. Phys. B **524** (1998) 3 [arXiv:hep-ph/9710401].
6. M. Dugan, B. Grinstein and L. J. Hall, Nucl. Phys. B **255** (1985) 413; S. Dimopoulos and S. D. Thomas, Nucl. Phys. B **465** (1996) 23 [arXiv:hep-ph/9510220].
7. A. Pilaftsis, Phys. Rev. D **58** (1998) 096010; Phys. Lett. B **435** (1998) 88.
8. A. Pilaftsis and C.E.M. Wagner, Nucl. Phys. B **553** (1999) 3; D.A. Demir, Phys. Rev. D **60** (1999) 055006; S.Y. Choi, M. Drees and J.S. Lee, Phys. Lett. B **481** (2000) 57; M. Carena, J. Ellis, A. Pilaftsis and C.E.M. Wagner, Nucl. Phys. **B586** (2000) 92; M. Carena, J. Ellis, A. Pilaftsis and C.E.M. Wagner, Nucl. Phys. **B625** (2002) 345.
9. J. S. Lee, A. Pilaftsis, M. Carena, S. Y. Choi, M. Drees, J. R. Ellis and C. E. M. Wagner, Comput. Phys. Commun. **156** (2004) 283 [arXiv:hep-ph/0307377].
10. J. S. Lee, M. Carena, J. Ellis, A. Pilaftsis and C. E. M. Wagner, arXiv:0712.2360 [hep-ph].
11. S. Heinemeyer, W. Hollik and G. Weiglein, *Comp. Phys. Comm.* **124** 2000 76, hep-ph/9812320; T. Hahn, S. Heinemeyer, W. Hollik, H. Rzehak and G. Weiglein, arXiv:0710.4891 [hep-ph].
12. M. Carena, J. R. Ellis, A. Pilaftsis and C. E. M. Wagner, Phys. Lett. B **495** (2000) 155 [arXiv:hep-ph/0009212].
13. E. Accomando *et al.*, arXiv:hep-ph/0608079.
14. S. Y. Choi and J. S. Lee, Phys. Rev. D **61** (1999) 015003 [arXiv:hep-ph/9907496]; S. Y. Choi, K. Hagiwara and J. S. Lee, Phys. Rev. D **64** (2001) 032004 [arXiv:hep-ph/0103294]; S. Y. Choi, M. Drees, J. S. Lee and J. Song, Eur. Phys. J. C **25** (2002) 307 [arXiv:hep-ph/0204200].
15. S. Schael *et al.* [ALEPH Collaboration and DELPHI Collaboration and L3 Collaboration and], Eur. Phys. J. C **47** (2006) 547 [arXiv:hep-ex/0602042].
16. M. S. Carena, J. R. Ellis, S. Mrenna, A. Pilaftsis and C. E. M. Wagner, Nucl. Phys. B **659** (2003) 145 [arXiv:hep-ph/0211467]; See also M. Schumacher in Ref. [13].
17. See P. Bechtle in Ref. [13].
18. F. Borzumati, J. S. Lee and W. Y. Song, Phys. Lett. B **595** (2004) 347 [arXiv:hep-ph/0401024].
19. The Atlas Collaboration, CERN-LHCC-99-15, ATLAS-TDR-15 (1999); G. L. Bayatian *et al.* [CMS Collaboration], J. Phys. G **34** (2007) 995.
20. F. Borzumati and J. S. Lee, Phys. Lett. B **641** (2006) 486 [arXiv:hep-ph/0605273].
21. J. Ellis, J. S. Lee and A. Pilaftsis, arXiv:0808.1819 [hep-ph].
22. B. C. Regan, E. D. Commins, C. J. Schmidt and D. DeMille, Phys. Rev. Lett. **88** (2002) 071805.
23. C. A. Baker *et al.*, Phys. Rev. Lett. **97** (2006) 131801 [arXiv:hep-ex/0602020].
24. M. V. Romalis, W. C. Griffith and E. N. Fortson, Phys. Rev. Lett. **86** (2001) 2505 [arXiv:hep-ex/0012001].
25. J. S. Lee and S. Scopel, Phys. Rev. D **75** (2007) 075001 [arXiv:hep-ph/0701221].
26. J. R. Ellis, J. S. Lee and A. Pilaftsis, Phys. Rev. D **70** (2004) 075010 [arXiv:hep-ph/0404167].
27. K. Kiers, A. Szynkman and D. London, Phys. Rev. D **74** (2006) 035004 [arXiv:hep-ph/0605123].